EXPLORING THE CHEMICAL AND STRUCTURAL PERFORMANCE OF SELF-COMPACTING LIGHTWEIGHT CONCRETE INCORPORATING PERLITE

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Abstract

This research focuses on the development and assessment of self-compacting lightweight concrete conforming to IS codes. The concrete mix incorporates perlite powder as a pozzolan, leveraging natural perlite as both coarse and fine aggregates. The study encompasses a series of tests to thoroughly examine the concrete's properties and performance.

Fresh properties evaluation includes measurements of slump, slump flow, unit weight, air content, and setting time, providing crucial insights into workability and consistency. Moving to hardened properties, the structural performance will be analyzed by assessing mechanical properties like compressive strength, splitting tensile strength, flexural tensile strength, modulus of elasticity.

Furthermore, durability characteristics will be investigated through rigorous testing methodologies. The concrete's resistance to chloride ingress will be determined via rapid chloride-ion penetrability tests. Additionally, its resilience against aggressive chemical solutions—such as sulphuric acid, magnesium sulphate, and sodium bicarbonate—will be thoroughly examined.

A comparative analysis will be conducted with conventional normal weight concrete to gauge the performance and superiority of the developed lightweight concrete. This comprehensive study aims to provide valuable insights into the viability and potential applications of self-compacting lightweight concrete in construction practices, emphasizing its mechanical strength and durability compared to conventional counterparts.

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1. Introduction

The construction industry has experienced a rapid surge in the adoption of lightweight aggregate concrete (LWAC) due to its distinct economic and technical advantages. Notably, LWAC offers reduced density, heightened specific strength, and improved durability, contributing to its growing popularity. This decreased density effectively lessens the structural elements' cross-sections and mitigates the vulnerability of buildings to seismic damage.

However, despite these benefits, the lower particle strength of the lightweight aggregate (LWA) in LWAC allows cracks to propagate through the aggregates rather than deflecting around them. Consequently, LWAC tends to exhibit higher brittleness compared to normal weight concrete (NWC) when reaching comparable strengths, restraining its broader utilization in structural applications.

In today's construction landscape, the selection of construction materials pivots significantly on their ability to perform sustainably in the face of climate change (Mehta & Monterio, 2016). The performance assessment of structural components under evolving environmental conditions stands pivotal in determining their usefulness, especially when these elements are subjected to substantial loads. The durability and strength of concrete have solidified its longstanding prominence in construction due to its resilience against environmental stressors, load-bearing capacity, extended service life, and manufacturing convenience. The development of lightweight concrete, with its reduced unit weight, enhances the strength-to-weight ratio, elevating its value as a structural material. As aggregates constitute a substantial portion of concrete, using lightweight aggregates results in low-density concrete both in its fresh and hardened states (Mehta & Monterio 2016; Mindess et al., 2003).

ACI Committee 213 and ASTM C330 outline various aggregate types with specific density and strength requirements for lightweight aggregate concrete (LWAC) production (213, A.C., 2014; ASTM, 2017). LWAC crafted from expanded shale, clay, or slate typically exhibits unit weights ranging from 1360 to 1840 kg/m³ (213, A.C., 2014) (Mindess et al., 2003; Neville, 2011). Such a weight range equates to a strength-to-weight ratio of about 64, marking a substantial increase from the ratio of 20 for conventional concrete. Given adequate compressive strength, LWAC emerges as a material of choice for structural concrete.

Recent times have seen LWAC gain traction as a popular construction material owing to its notably lower density and thermal conductivity compared to concrete made with normal-weight aggregate (NWA) referred to as NWAC. A significant portion of structural load in built infrastructure comprises dead load, which includes a substantial portion as the self-weight of these elements. Thus, reducing the self-weight of structural members holds immense significance, allowing the design of smaller cross-sections that are economically lighter. LWAC serves as the material of choice when aiming for reduced dead load in concrete structural members and improved thermal insulation properties (Darwin et al., 2016; Mehta & Monterio, 2016; Zhou & Brooks, 2019).

The merits of LWAC extend beyond weight reduction and insulation; they include enhanced freeze-thaw performance, excellent acoustic insulation, superior performance under dynamic loading, reduced structural member deflection, and ease of production (Libre et al., 2011; Tajra et al., 2019; Wu et al., 2019; X.F. Wang, Fang, Kuang, Li, Han, Xing et al., 2017a). LWAC production can employ both naturally occurring lightweight aggregates (LWA) and artificially produced lightweight aggregates. Despite limitations in its strength, successful reports highlight the use of LWA as partial replacements for NWA in concrete mixtures (Rumsys et al., 2018; Tajra et al., 2019; Wongsa et al., 2018; X.F. Wang et al., 2018).

1.1Self-Compacting Concrete

Self-compacting concrete, alternatively known as Self-Consolidating Concrete (SCC) or High-Performance Concrete, emerged from research conducted at the University of Tokyo in the 1980s. This specialized type of concrete, distinct for its high fluidity eliminating the need for vibration during placement, relies on a combination of mineral and chemical admixtures. By leveraging these additives, self-compacting concrete achieves a dense state under its own gravitational force, effortlessly filling formwork even in the presence of dense steel reinforcement.

Noteworthy for its resistance to segregation and ease of filling, this concrete exhibit exceptional flow properties, making it ideal for intricate shapes and densely reinforced sections. Maintaining its homogeneity throughout transportation and placement, self-compacting concrete embodies high fluidity and superior deformability, meeting stringent requirements for concrete strength, volume stability, and durability (Wu et al., 2015).

Primarily suited for mass concrete applications due to its superior workability, self-compacting concrete relies on superplasticizers, reactive powder, and viscosity enhancers to retain its deformability and cohesiveness (Prakash et al., 2021). However, the increased use of powders in its composition results in smaller pores and reduced available water, culminating in significant self-shrinkage and the potential for early concrete cracking (Zhang et al., 2003). Balancing workability and shrinkage become crucial in ensuring the optimal performance of self-compacting concrete.

2. Experiment Design

The primary objective of this study was to conduct an experimental study aimed at the design of self-compacting lightweight concrete. A crucial aspect of this study was to compare the mechanical properties and durability characteristics of this lightweight concretes with those of a normal weight concrete possessing a similar specific strength. To achieve this objective, two distinct concrete mixtures were meticulously prepared and their compositions were carefully formulated to ensure comparable specific strength at the 28th day of curing. This approach enabled the establishment of a reference point for subsequent analysis and comparison of the test results.

A mixture was designed as a self-compacting high-strength lightweight concrete, incorporating high volume perlite powder as a pozzolan, in addition to natural perlite as the coarse and fine aggregate. Second mixture was prepared as a high-strength normal weight concrete, utilizing limestone aggregate.

Throughout the course of this study, various essential properties of the concrete specimens were thoroughly investigated. The investigation encompassed both fresh properties, such as slump, slump flow, unit weight, and setting time, as well as hardened properties, including compressive strength, splitting tensile strength, flexural tensile strength, elastic modulus, and thermal coefficient of expansion. Furthermore, an examination of the durability characteristics of the concrete samples was conducted, specifically focusing on their resistance to rapid chloride ion penetration, exposure to aggressive chemical solutions.

2.1Objectives

A self-compacting light weight concrete will be designed as per IS codes, using perlite powder as pozzolan and natural perlite as coarse as well as fine aggregate and then performing following tests:

1. Fresh Properties: The fresh properties of the lightweight concrete, such as slump, slump flow, unit weight, air content, and setting time, will be measured to assess workability and consistency.
2. Hardened Properties: The hardened properties of the lightweight concrete will be evaluated to determine its structural performance. The evaluation of the material's mechanical properties and structural behaviour will involve measuring parameters such as compressive strength, splitting tensile strength, flexural tensile strength, modulus of elasticity.
3. Durability Characteristics: The durability of the lightweight concrete will be evaluated through various tests. Rapid chloride-ion penetrability will be assessed to determine the concrete's resistance to chloride ingress. Additionally, the lightweight concrete's resistance to aggressive chemical solutions, such as sulphuric acid, magnesium sulphate, and sodium bicarbonate, will be examined.
4. Comparison of this prepared self-compacting lightweight concrete will be done with the normal weight concrete.

3. Mix Proportion for Self-Compacting Lightweight Concrete (SCLWC)

By following the mix design procedure mentioned in IS code 10262-2009, following proportion for various aggregates was calculated:

• Cement	240 Kg/m^3
• Perlite	240 Kg/m^3
• Water	128 Kg/m^3
• Fine aggregate	667 Kg/m^3
• Coarse Aggregate	771 Kg/m^3
• Superplasticizer	7 Kg/m^3
• Water – cement ration	0.27

Mix Proportion High Strength Normal Weight Concrete (HSNWC)

• Cement	320 Kg/m^3
• Water	128 Kg/m^3
• Fine aggregate	921 Kg/m^3
• Coarse Aggregate	1173 Kg/m^3
• Superplasticizer	7 Kg/m^3
• Water – cement ration	0.4

3.1Method to calculate various properties

Workability:

The slump cone test is adapted to measure workability which is universally accepted and is simple in operation. The test procedure specified in IS 1199 – 1959.

Compressive Strength

The compressive strength of the specimen was determined on 7th, 28th, 90th and 365th day in accordance with IS 516 – 1959 to study the development of strength at later ages.

Flexural Strength

The flexural strength of concrete is determined by subjecting a plain concrete beam to flexure under transverse loads. Two-point load method is adopted to measure the flexural strength, as per IS 9399 (1979) and using the following equation

$$\text{Modulus of rupture, } f_b = \frac{PL}{bd^2},$$

where, P is the maximum load applied, N
L is the supported length of the specimen, mm
b is the measured width of the specimen, mm and
d is the measured depth of the specimen, mm

Modulus of Elasticity: As per the specification mentioned in IS 516 – 1959.

Splitting tensile strength: As determined as per IS 5816 (1999) and using

$$\text{Split Tensile Strength, } f_{sp} = \frac{2P}{\pi DL},$$

where, P is the Maximum compressive load in the cylinder, N
L is the length of cylinder, mm and
D is the diameter, mm.

RCPT test: As per ASTM C 1202 to determine the electrical conductance of the mixes at the age of 28 days, 56 days and 90 days of curing

Reaction to Aggressive Chemical Solution: MgSo4 Solution test, H2SO4 Sol test, NaHCO3 Solution – By dipping the specimens in the solution for sufficient time and then measuring the value.

4. Results:

4.1Slump, Setting Time

As stated earlier, two types of concretes were designed. The mix design for M40 concrete was established in accordance with IS 10262-2009. Based on the characteristics of the cement, fine aggregates, and coarse aggregates, superplasticizers were incorporated with the corresponding water-to-cement ratio.

Two types of concrete are self-compacting high strength lightweight concrete (SCLWC) and high-strength normal weight concrete (HSNWC). The mix proportions and fresh properties are as shown in Table 4.1.

Table 4.1 Mix proportions and fresh concrete properties

Mix Proportions (kg/m^3)		
Concrete Type	**SCLWC**	**HSNWC**
Cement	240	320
Perlite Powder	240	
Water	128	128
Aggregates		
0-4 mm PA / 0-5 mm LA (SSD)	790 / 0	0 / 1194
4-8 mm PA / 5-15 mm LA (SSD)	361 / 0	0 / 481
8-12 mm PA / 15-25 mm LA (SSD)	287 / 0	0 / 419
Superplasticizer	7	7
water cement ratio	0.27	0.4
Theoretical Fresh Concrete Density (kg/m^3)	2053	2549
Fresh Properties		
Measured Fresh Density (kg/m^3)	1984	2492
Air Content	2.2	2.2
Slump		9
Setting Time		
Initial Setting (hr:min)	4:00	4:30
Final Setting (hr:min)	7:00	7:30

As shown in the table above, SCLWC has approximately 80 kg/m^3 less cement content when compared to HSNWC, however it also contains perlite powder as pozzolan and when its total binder content is considered, it almost double than the other two types of concretes. SCLWC can also be named as self-compacting high volume pozzolan concrete since 50% of its binding medium is pozzolan.

It is hard to define an exact w/c ratio for lightweight concretes, since the absorption capacity of lightweight aggregates are high and the water absorption can continue for several weeks. Nevertheless, using the 3-days absorption capacity data of perlite aggregates, w/cm ratios have been estimated. It was found that SCLWC has a w/cm ratio of 0.27. The ratio may seem to be relatively low, however to obtain high strength lightweight concretes, it is a necessity. Unlike lightweight aggregate concretes, the determination of w/c ratio for concretes with normal weight aggregates are more accurate and reliable. HSNWC was designed with a w/c ratio of 0.40.

The measured fresh densities are lower than the theoretical ones. The difference between theoretical and measured fresh densities is around 69 kg/m^3 for SCLWC whereas it is 57 kg/m^3 for HSNWC.

Initial and final setting time of the concretes produced are also given in Table 4.1. The shortest setting time is measured for SCLWC, which has the highest binder content and lowest w/b ratio.

4.2Compressive Strength, Density and Specific Strength

As stated previously, the mix proportions are determined such that 28th day specific strengths of all three designed concrete types would be comparable. Since the concrete in structural applications is generally air-dry in-service condition, specific strength calculations are based on air-dry density of the specimens.

In Table 4.2, compressive strength, specific strength, unit weight of the designed concretes in saturated surface dry (SSD), air-dry (AD) and oven-dry (OD) condition have been provided.

Table 4.2 Compressive Strength, density and specific strength

Compressive Strength (MPa)		
Age	**SCLWC**	**HSNWC**
7 Days	36.9	49.7
28 Days	50.9	54.9
56 Days	52.6	57.3
90 Days	55.4	57.7
120 Days	59.6	58.2
180 Days	64.9	59.9
270 Days	67.2	63.2
Density (kg/m^3)		
Moisture Condition	**SCLWC**	**HSNWC**
SSD	2041	2533
AD	2015	2499
OD	1959	2444
Specific Strength (MPa tons/m^3)		
Moisture Condition	**SCLWC**	**HSNWC**
AD	25.7	23.1

As for SCLWC, although the rate of strength development slows down after 28 days, it steadily continues to increase even after 90 days, thanks to the pozzolanic activity of perlite.

The densities of the designed concretes were measured under three conditions: saturated surface dry (SSD), air-dry (AD), and oven-dry (OD) conditions, as shown in Table 4.2. When classifying concretes based on their weights, the air-dry equilibrium density is considered. SCLWC has a slightly higher density (around 2015 kg/m3), which exceeds this definition by about 95 kg/m^3. It is important to note that while ACI Committee 213 (2003) provides a range of densities, it does not set specific specifications. Job specifications may permit higher densities to achieve a desired combination of strength and density in a cost-effective manner. Additionally, the oven-dry density of SCLWC is 1959 kg/m^3, which is higher than its air-dry density of 2015 kg/m^3 but still below the 2000 kg/m^3 limit defined by EN206-1:2000. Comparing the air-dry densities SCLWC is 19% lighter than HSNWC.

4.3 Splitting and Flexural Tensile Strength

The splitting and flexural tensile strength of the designed concretes at 28 and 90 days of age are presented in Table 4.3. The results indicate that

SCLWC exhibit splitting tensile strength and flexural tensile strength values that are approximately 1-2 MPa lower than those of HSNWC, despite having similar specific strength. Furthermore, the data suggests that there is no significant increase in tensile strength between 28 and 90 days.

Table 4.3 Splitting and flexural tensile strength

Splitting Tensile Strength (MPa)		
Age	**SCLWC**	**HSNWC**
28 Days	4.2	4.3
90 Days	4.3	5.2
Flexural Tensile Strength (MPa)		
Age	**SCLWC**	**HSNWC**
28 Days	6.1	7.9
90 Days	6.2	8.1

4.4. Elastic Modulus

Table 4.4 Modulus of elasticity, compressive strength & density

Elastic Modulus (GPa)		
Age	**SCLWC**	**HSNWC**
28 Days	26	44.9
90 Days	25.9	42.5
Compressive Strength (MPa)		
Age	**SCLWC**	**HSNWC**
28 Days	6.1	54.9
90 Days	6.2	57.6
Density (kg/m^3)		
Moisture Condition	**SCLWC**	**HSNWC**
AD	1983	2376

Table 4.4 provides the elastic modulus values of the designed concretes at 28th and 90th days. It can be observed that there is negligible change in the elastic modulus between these two time periods. The elastic modulus of SCLWC is approximately 60% of HSNWC. This decrease in elastic modulus for lightweight concretes can be attributed to the lower stiffness of the natural perlite aggregates used.

Evaluation of Rapid Chloride Ion Penetrability

Table 4.5 Charges Passed(coulombs) - Chloride Ion Penetrability

Age(days)	SCLWC		HSNWC	
28	800	Very Low	3696	Moderate
90	271	Very Low	3054	Moderate

The outcomes of rapid chloride ion penetrability assessments are detailed in Table 4.5. After 28 days, the Super Low W/C concrete or self-compacting concrete displays very low penetrability. In contrast, the High Strength Normal W/C concrete showcases moderate penetrability. These findings align with expectations. The Super Low W/C concrete, with the highest binder content and the lowest w/cm ratio among the three types, demonstrated the least penetrability. Pozzolanic activity significantly contributed to this outcome.

By the 90-day mark, the chloride ion penetrability of the Super Low W/C concrete decreased to one-third. However, the reduction in penetrability of the High Strength Normal W/C concrete was only around 20%.

4.5 Investigation of Specimens in Harsh Chemical Solutions

4.5.1. Evaluation in Magnesium Sulphate Solution

The alterations in compressive strength for specimens immersed in a 0.352 M $MgSO_4$ solution are visually presented in Figures 4.1 and 4.2, each graph dedicated to a specific concrete type. Notably, the line representing the control group and the line depicting specimens in the magnesium sulphate solution almost overlap in all graphs. This indicates that Super Low W/C (SCLWC), and High Strength Normal W/C (HSNWC) exhibit similar resistance to sulphate attack, especially evident when considering the change in compressive strength.

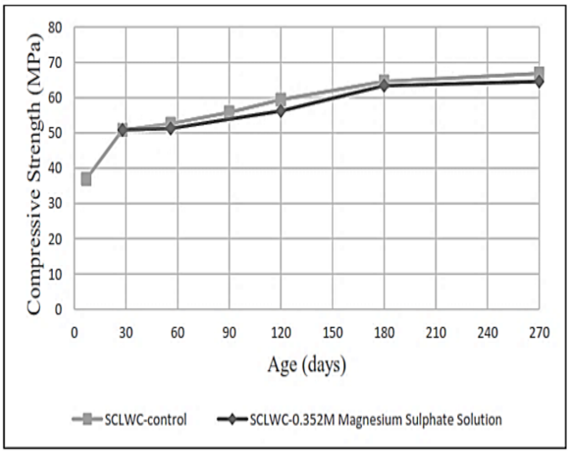

Figure 4.1. Change in compressive strength of SCLWC specimens stored in magnesium sulphate solution

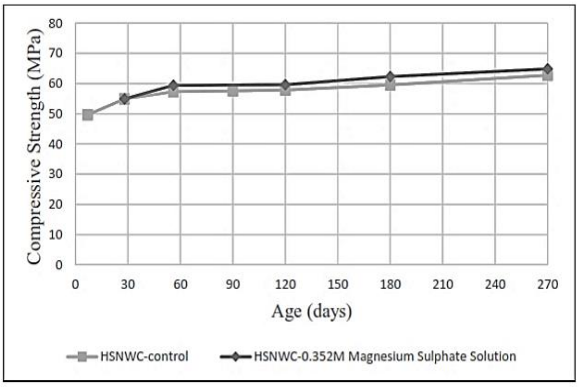

Figure 4.2. Change in compressive strength of HSNWC specimens stored in magnesium sulphate solution

Figures 4.3 and 4.4 showcase the surface deterioration of specimens exposed to the magnesium sulphate solution. The observations suggest that the surface deterioration of HSLWC and SCLWC is relatively more pronounced compared to HSNWC.

Figure 4.3. Surface deterioration of SCLWC specimens stored in magnesium sulphate solution

Figure 4.4. Surface deterioration of HSNWC specimens stored in magnesium sulphate solution

4.5.2 Evaluation in Sodium Bicarbonate Solution

The impact of carbonation on concrete is highlighted, where it doesn't result in detrimental deterioration but alters the pH of the concrete pore solution. This process affects reinforced concrete by causing the loss of the passive layer that shields rebars from corrosion. However, carbonation also brings about positive consequences such as heightened surface hardness and strength, along with reduced surface permeability. This is primarily due to the conversion of calcium hydroxide to calcium carbonate, which occupies more space and fills concrete pores.

Figures 4.5 and 4.6 display the variations in compressive strength for specimens submerged in a 0.352M $NaHCO_3$ solution, categorized by concrete type. Notably, there isn't a significant strength increase observed in any of the concretes immersed in the solution. This lack of change indicates that all the concretes are adequately impermeable, and their interior zones remain unaffected.

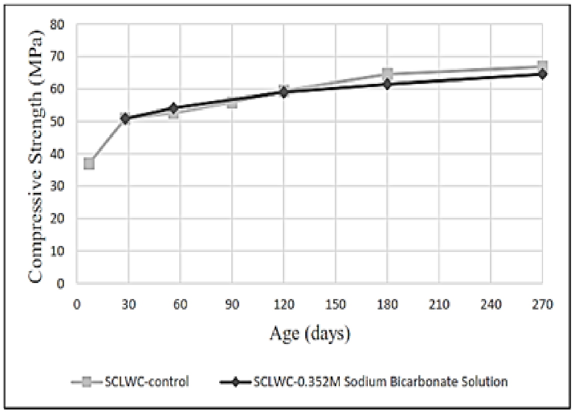

Figure 4.5. Change in compressive strength of SCLWC specimens stored in sodium bicarbonate solution

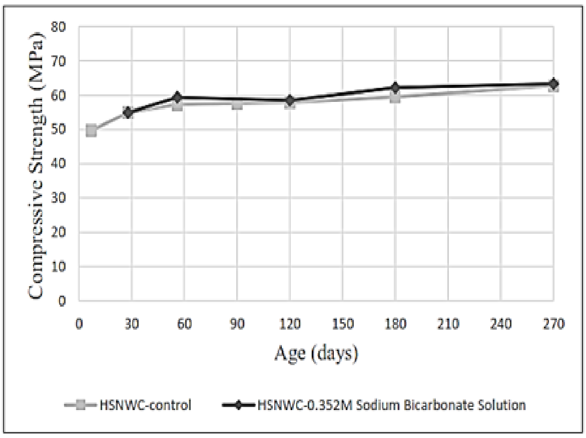

Figure 4.6. Change in compressive strength of HSNWC specimens stored in sodium bicarbonate solution

This was confirmed by the phenolphthalein test, which revealed a pH still higher than 9.5, indicated by the continued pink coloration when applied to the concrete. However, visually, it is evident that the surface of the specimens in the carbonate solution has become smoother and less porous due to surface carbonation.

In Figures 4.7 and 4.8, the carbonation effects on the surface of the specimens stored in the sodium bicarbonate solution, along with interior zones tested by phenolphthalein, are illustrated for further examination and comparison.

Figure 4.7. Surface deterioration of SCLWC specimens stored in sodium bicarbonate solution and interior of concrete tested by phenolphthalein

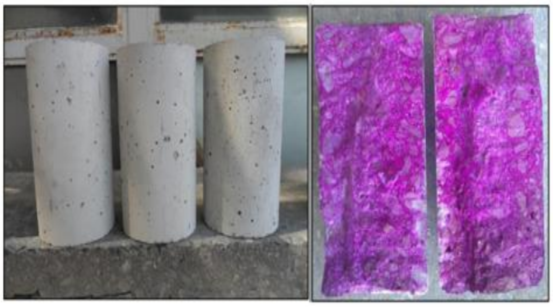

Figure 4.8. Surface deterioration of HSNWC specimens stored in sodium bicarbonate solution and interior of concrete tested by phenolphthalein

4.5.3 Evaluation in Sulphuric Acid Solution

The alterations in compressive strength for specimens immersed in a 1% H2SO4 solution (pH=1) are depicted in Figures 4.9 and 4.10, individually illustrating each type of concrete. Notably, for the initial three months of exposure, the line representing the control group closely aligns with the line representing the specimens in the sulphuric acid solution.

However, beyond this period, the specimens began to exhibit a decline in compressive strength. By the ninth month, the percentage losses in compressive strengths compared to the control specimens were 14%, and 0.4% for SCLWC, and HSNWC, respectively. This indicates that HSNWC displays greater durability against sulphuric acid compared to SCLWC.

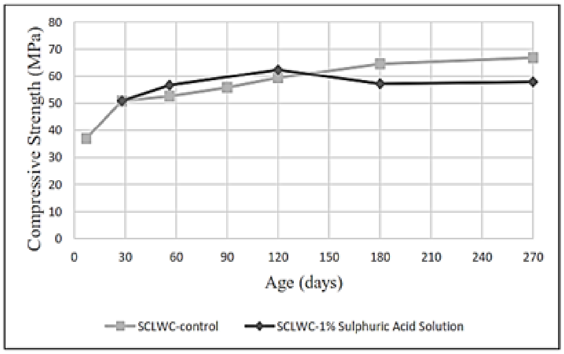

Figure 4.9. Change in compressive strength of SCLWC specimens stored in sulphuric acid solution

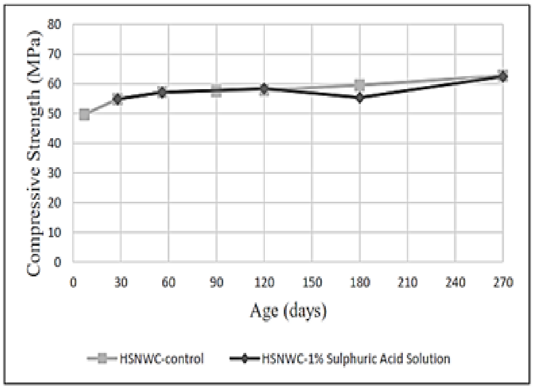

Figure 4.10. Change in compressive strength of HSNWC specimens stored in sulphuric acid solution

However, on individual evaluation, SCLWC can also be considered durable since its compressive strengths under such aggressive conditions still surpass the initial 28-day strength.

Figure 4.11. Surface deterioration of SCLWC specimens stored in sulphuric acid solution

Figures 4.11 and 4.12 illustrate the surface deterioration of specimens subjected to the sulphuric acid solution. The visuals indicate deterioration on the surface of all concretes. Additionally, weak cover formation was observed for SCLWC. By the end of an 8-month exposure period, this deteriorated cover had reached a thickness of 4 mm. This corresponds to a 15% reduction in load-bearing area, correlating with the strength reduction (12-14%) observed in these specific specimens.

Figure 4.12. Surface deterioration of HSNWC specimens stored in sulphuric acid solution

Conclusion

The experimental study within this thesis reveals pivotal insights into the utilization of natural perlite aggregate in the creation of high-performance lightweight concretes.

1. **Strength Potential:** Natural perlite aggregate exhibits promise, facilitating the production of high-performance lightweight concretes boasting remarkable 28-day compressive strengths of up to 50 MPa.
2. **Optimal Mix Characteristics:** By employing natural perlite aggregate alongside a high volume (50%) of perlite powder as a pozzolan, the study demonstrates the creation of self-compacting high-strength lightweight concretes. These concretes display excellent workability characteristics, enhancing their structural viability.
3. **Cement Requirements:** Achieving a comparable specific strength to that of high-strength normal weight concrete with natural perlite aggregate demands similar cement contents, approximately 300 kg/m^3.
4. **Weight Differential:** High-performance lightweight concretes incorporating natural perlite aggregate are approximately 20% lighter than high-strength normal weight concrete at similar specific strengths.
5. **Elastic Modulus Variation:** In contrast to high-strength normal weight concrete with limestone aggregate, high-performance lightweight concretes with natural perlite aggregate exhibit an elastic modulus reduced by about 50-60%. This discrepancy is attributed to the lower stiffness of lightweight aggregates, with the study validating the applicability of ACI 318 formula for estimating the elastic modulus of structural lightweight concretes with natural perlite aggregates.
6. **Chloride Permeability:** Lightweight concretes with natural perlite aggregate and perlite powder showcase significantly lower chloride permeability, around 20-10% at 28 and 90 days respectively compared to high-strength normal weight concrete. This superior performance stems from various factors, including a lower water-to-binder ratio, internal curing, and enhanced pozzolanic activity, leading to an improved contact zone.
7. **Durability in Various Environments:** Against magnesium sulphate attack, high-performance lightweight concretes with natural perlite aggregate display comparable durability to high-strength normal weight concrete concerning compressive strength changes. However, these lightweight concretes exhibit greater surface deterioration in magnesium sulphate solutions compared to limestone-containing high-strength normal weight concrete.

In essence, the experimental findings underscore the potential, structural characteristics, durability, and susceptibility to various environmental challenges of high-performance lightweight concretes incorporating natural perlite aggregate, offering invaluable insights for construction applications.

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